

Dense DM clumps seeded by cosmic string loops and DM annihilation

V.S. Berezinsky,^{a,b} V.I. Dokuchaev^c Yu.N. Eroshenko^c

^aINFN, Laboratori Nazionali del Gran Sasso, I-67010 Assergi (AQ), Italy

^bCenter for Astroparticle Physics at LNGS (CFA), I-67010 Assergi (AQ), Italy

^cInstitute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

E-mail: berezinsky@lngs.infn.it, dokuchaev@inr.ac.ru, eroshenko@inr.ac.ru

Abstract. We develop a model of production of the very dense clumps of DM in RD epoch due to the accretion of DM on the loops of cosmic strings as the seeds. At some time the loops disappear, for example due to the gravitational radiation, and the remaining dense clumps produce the enhancement of the annihilation signal. We take into account the velocity distribution of the strings, and consider the two extreme regimes of DM annihilation: fast decay and continuous evaporation. The produced annihilation flux of gamma radiation is detectable, and for some parameters of DM particles and the strings can exceed the extragalactic flux of the gamma-radiation observed by Fermi. For the fixed parameters of DM particles (e.g. neutralino with fixed masses and cross-section of annihilation) one can obtain the limits on the basic string parameter, tension μ , which is stronger than (more general) limits obtained from WMAP observations, cosmological nucleosynthesis and gravitational lensing. In particular for the neutralino with 100 GeV mass we exclude the interval $5 \times 10^{-10} < G\mu/c^2 < 5.1 \times 10^{-9}$.

Keywords: dark matter, cosmic string, cosmology

Contents

1	Introduction	2
2	Initial speed of the loops and rocket effect	3
3	Evolution of clumps around evaporating loops	4
4	Continuous evaporation and fast decay approximations	4
5	Numerical results	6
6	Loops and clumps distributions	7
7	DM annihilation	8

1 Introduction

The linear topological defects — cosmic strings can be formed in the early cosmological phase transitions (see for a review [1], [2]). Along with the infinite strings there is possibility of closed loops formation in the network of curved cosmic strings due to their interconnections. According to numerical simulations, after a long transient stage a true scaling regime sustained, then the typical distances between the strings and the coherence length both scale in proportion with the horizon scale [3]. A string loop formed at the cosmological time t_i has the length $l \simeq \alpha c t_i$, where in the scaling regime $\alpha \simeq 0.1$ according to [3] and [4], although other values of α were obtained in other works (see for example [5], [6]), down to $\alpha \sim 10^{-3}$.

A fundamental characteristic of the string is the mass per unit length $\mu \equiv M_l/l$ or the tension, which is of the order of symmetry breaking energy squared η^2 . For example, the grand-unification-scale strings have $G\mu/c^2 \sim 10^{-6}$, where G is the Newton's constant. There are several restrictions on μ . From CMB observations it follows $G\mu/c^2 \leq 2 \times 10^{-7}$ [7]. The bound $G\mu/c^2 \leq 10^{-7}$ was obtained from the study of nucleosynthesis [3]. Search for the pairs of galaxies images consistent with the gravitational lensing of the cosmic string presents the limit $G\mu/c^2 < 3 \times 10^{-7}$ at 95% confidence level [8]. In [9] the formation of stars in the first dark matter DM haloes seeded by the loops was considered. It was found that $G\mu/c^2 < 3 \times 10^{-8}$ to avoid collision with WMAP data on the reionization redshift. Searches for the gravitational wave bursts from strings by LIGO provide the joint constraints on the strings parameters (μ and interconnection probability) [10], but $G\mu/c^2$ is only weakly restricted in comparison with the constraints above. And finally, the strongest bound $G\mu/c^2 \leq 4 \times 10^{-9}$ was obtained from the pulsar timing [11].

In this work we present new constraint on μ which was obtained from the DM particles annihilation in the dense clumps seeded by the loops at the cosmological stage of radiation dominance. The direct detections of DM particles are the promising but still elusive experimental problems, therefore the search of indirect signature of the DM is important for clarifying the DM origin. The promising indirect signature — DM particles annihilation would proceed more efficiently (it can be boosted by several orders) if the Galactic halo is filled by the dense DM substructures or DM clumps. The cosmic string loops produce very dense clumps due to their early formation. Only low velocity loops can produce the clumps. The probability of the low velocity loop formation is very small, but even tiny fraction of the formed loops may produce the dense clump population and significant annihilation signal.

The clumps formation at the radiation dominated (RD) stage was studied in details by [12]. In the particular case of loops' density perturbations the maximum density of clump is restricted due to adiabatic expansion of the already formed clump after the loop gravitational evaporation. We found the modification of this restriction in the case then the loop decays before the clump virialization. In this case the clumps can reach density $\rho_{cl} \gg 140\rho_{eq}$, where ρ_{eq} is the density at equality. The comparison of the resulting annihilation signal with the Fermi-LAT data allows us to obtain the restriction on the string parameter μ . It must be pointed out that our constraints were obtained by supposing that the DM can annihilate, and we take the ~ 100 GeV neutralino as the most promising particle candidate. The constraints will be different for other DM models. In this sense the obtained constraints must be considered as joint constraints on the properties of the string loops and DM particles.

2 Initial speed of the loops and rocket effect

Here we consider the influence of the initial velocities of the loops and rocket effect on the evolution of perturbations and clumps formation.

The necessary condition for the clump formation is the low velocity of the loop [12]. Only results for average initial velocity of formed loops were presented in literature but the distribution over velocities is possible. We interested in low velocity end of the distribution, because the clump forms only if the seed loop stays near the center of the clump during its evolution. Loops can be formed by intersecting long string segments or by self-intersection of long strings. We suppose that the probability of velocity components of the loops is simply Gaussian with mean value at the correlation length scale $\langle v_i^2 \rangle^{1/2} \simeq 0.15c$ [13], and therefore the probability of full initial velocity is

$$P(v_i)dv_i \simeq \frac{2^{1/2}dv_i v_i^2}{\pi^{1/2}\langle v_i^2 \rangle^{3/2}} e^{-v_i^2/2\langle v_i^2 \rangle}. \quad (2.1)$$

Even if the process of a loop's formation involves the intersection of two strings with large velocities, it does not necessarily means that the resulting velocity will be high.

The displacement of the loop beginning from its birth moment t_i till the full decay moment t_d is

$$\Delta r = a(t_d) \int_{t_i}^{t_d} \frac{v(t)dt}{a(t)}, \quad (2.2)$$

where the peculiar velocity is $v(t) = v_i a(t_i)/a(t)$. We require that the displacement Δr is smaller in comparison with the loop's radius $l/(2\pi)$. From this condition and (2.2) we obtain the restriction on the loop's velocity

$$v_i t_i \ln(t_d/t_i) < l/(2\pi). \quad (2.3)$$

For the probable parameters of the strings $t_d/t_i \simeq 2 \times 10^5$ and the dependence in (2.3) is only logarithmic. Therefore, by using (2.1) we can estimate the probability of the low velocity loop formation as

$$P_{lv} \sim \frac{(2/\pi)^{1/2} v_i^3}{3\langle v_i^2 \rangle^{3/2}} \simeq 2 \times 10^{-7}. \quad (2.4)$$

As we will show below even the tiny fraction (2.4) of the formed loops may produce superdense clumps and observable annihilation signals.

Now we consider the rocket effect. Velocity of the loop grows linearly with time $v_r = 3\Gamma_P G\mu t/(5l)$, where $\Gamma_P \sim 10$ [1]. Turnaround moment of the clump corresponds to $t_{TA}^2 \simeq 500t_i^2$, and the relative displacement of the loop during clump formation is

$$\frac{1}{l} \int_{t_i}^{t_{TA}} v_r dt \simeq 1.5 \times 10^{-4} \mu_{-8} \alpha_{0.1}^{-1} \ll 1, \quad (2.5)$$

where $\mu_{-8} \equiv G\mu/(10^{-8}c^2)$. Therefore, for the small loops formed at radiation era the large rocket displacements are not achieved.

3 Evolution of clumps around evaporating loops

We solve the same equation as eq. (2.7) in [12]

$$x(x+1)\frac{d^2b}{dx^2} + \left[1 + \frac{3}{2}x\right]\frac{db}{dx} + \frac{1}{2}\left[\frac{1+\Phi}{b^2} - b\right] = 0, \quad (3.1)$$

where $x = a(t)/a_{\text{eq}}$ is used as independent variable, $r = ab(x)\xi$ is the physical radius of the spherical shell and ξ is its comoving coordinate, Φ is the density perturbation of DM $\delta\rho/\bar{\rho}$ inside the spherical shell. This equation describes the evolution of the clump's radius r in terms of the function $b(x)$. The only quantity one need to modify is the Φ . In difference with [12] we allow the dependence of Φ on the time: steady decrease in the continuous evaporation approximation and step-like in the fast decay approximation. The evolution of clump stops when $dr/dt = 0$ or equivalently $db/dx = -b/x$ [12]. The density and the radius of the clump at the moment of its maximum expansion are

$$\rho_{\text{max}} = \rho_{\text{eq}} x_{\text{max}}^{-3} b_{\text{max}}^{-3}, \quad R_{\text{max}} = \left(\frac{3M}{4\pi\rho_{\text{max}}}\right)^{1/3}, \quad (3.2)$$

where b_{max} and x_{max} are the values at the moment of the stop. After the turnaround the clump virializes by contracting twice in radius, and the resulting density increases by factor 8 in comparison with (3.2).

Let us name the spherical region with a volume $(4\pi/3) \cdot (l/2\pi)^3$ as a “string volume”. Then the fraction of string mass $M_l = \mu l$ to the mass M_{DM}^l of DM inside the string volume at the moment of the string birth $t_i = l/(\alpha c)$ is simply

$$\left.\frac{M_l}{M_{\text{DM}}^l}\right|_{t=t_i} = \left(\frac{M_l}{M_\beta}\right)^{-1/2}, \quad (3.3)$$

where $M_\beta = 1.6 \times 10^3 \mu_{-8}^3 \alpha_{0.1}^{-3} M_\odot$. The (3.3) was calculated from the law of DM density evolution $\propto a^{-3}$ according to the known solutions of the Friedmann equations. The fraction (3.3) gives also the value Φ of the density perturbation inside the string volume at the moment of string birth t_i , and in the most interesting cases $\Phi \gg 1$, with the production of the superdense clumps. The strings with $M_l = M_{\text{DM}}^l(t = t_i)$ born at the time $t_\beta = 3.9 \times 10^{-6} \mu_{-8}^2 \alpha_{0.1}^{-4} t_{\text{eq}}$ ($x_\beta = 2 \times 10^{-3} \mu_{-8} \alpha_{0.1}^{-2}$). We consider only the most dense central part of the clump inside the string volume, where the annihilation proceeds most effectively. This central region of the clump can be refereed as a clump core. The oscillation of string itself does not distort the core because the linear segment of the string has small gravitational potential. The only common (mean over the string volume) potential of the loop attracts the DM. The outer regions of the clump form through the secondary accretion of DM and have the density profile $\rho(r) \propto r^{-9/4}$ at the sufficiently high distance from the center of the clump. Therefore the annihilation concentrates near the clump core.

4 Continuous evaporation and fast decay approximations

The characteristic loop lifetime due to gravitational waves emission is $\tau \simeq lc/(G\mu\Gamma)$, where $\Gamma \sim 50$ is a numerical coefficient [14]. One possibility is that the loop losses mass continuously according to mean equation $dM_l/dt = -\Gamma G\mu^2/c$, but the more reliable approach is to assume

the sudden decay after the time interval τ from the birth moment t_i . At $t > t_i + \tau$ the loop's configuration substantially changed, so the loop is likely to self intersect. The resulting daughter loops will fly away at high speeds. We use the last approximation henceforth as the main but also present the results for the continuous evaporation approximation for comparison.

DM clumps formation at the RD stage was explored in [12]. In the particular case for the clumps which are seeded by loops of cosmic strings one have $\Phi \simeq M_l/M$, but in many cases the maximum density is only $\rho_{\text{cl}} \simeq 140\rho_{\text{eq}}$ due to adiabatic expansion of already formed clump during the seed loop gravitational evaporation [12]. Really, the universal Poincare adiabatic invariant conservation $J = \oint \sum p_i dq_i = \text{const}$ for the clump with additional loop mass inside implies $M_{\text{tot}}R = \text{const}$ or $\rho_{\text{cl}} \propto M_{\text{tot}}^{-3}$, where $M_{\text{tot}} = M_l(t) + M_{\text{DM}}$ is the total mass of the loop and DM. For the constant mass loop the clump forms with the density $\rho_{\text{cl}} \simeq 140\rho_{\text{eq}}(M_l/M_{\text{DM}})^3$ (see eq. (3.4) in [12]). After the subsequent loop decay the density lowered due to adiabatic invariant in proportion $\simeq (M_{\text{DM}}/M_l)^3$ till the value $\rho_{\text{cl}} \simeq 140\rho_{\text{eq}}$.

We argue that the above mentioned argument of the adiabatic invariant conservation is not applicable, if the loop decay occurs before turnaround moment (detachment from the cosmological expansion and the clump virialization). Really, in this case DM particles move not at the orbits around the loop but along the radial trajectories. The loop's decay leads only to the change of the particles acceleration. The evolution of clump slows down but continues under the influence of velocities db/dt obtained before the decay. We can estimate the processes by the following manner. For the clumps under consideration the conditions $x \ll 1$, $\Phi \gg 1$ and $\Phi x \ll 1$ are valid almost all the time before turnaround. Initially the evolution goes due to large value of Φ and the initial velocities db/dx at $t = t_i$ are not important. At this stage one can neglect the first term in (3.1) and the approximate solution is $b \simeq 1 - x\Phi/2$ [12]. If the turnaround occurs before t_d the moment of turnaround can be estimated as $x_{\text{TA}} \sim 1/\Phi$ [12]. In the opposite case $x_d < x_{\text{TA}}$ just after loop decay (at $x = x_d$) we must put $\Phi = 0$ in (3.1) and the velocity at this moment $db/dx = -\Phi/2$ becomes greater then the last term in (3.1). At $x > x_d$ we can neglect the last term but leave the first one. This leads to the red-shifting of velocity as

$$\frac{db}{dx} = -\frac{\Phi x_d}{2x} \quad (4.1)$$

and to the corresponding logarithmic decrease of b . From the condition $db/dx = -b/x$ we obtain the new turnaround moment:

$$x_{\text{TA}} \sim x_d \exp\left(\frac{2(1 - \Phi x_d)}{\Phi x_d}\right). \quad (4.2)$$

We see that at the sufficiently small $\Phi x_d \ll 1$ the clump may not forms at all, because the x_{TA} will be exponentially large. For the moderately small values $\Phi x_d \ll 1$ the clump forms but with small density. The value Φx_d can be expressed as

$$\Phi x_d \simeq 0.9\mu_{-8}^{1/2}\alpha_{0.1}^{-3/2}\Gamma_{50}^{-1/2}. \quad (4.3)$$

For the constant mass loop $x_{\text{TA}} \sim 1/\Phi$ [12] and (4.3) is $\sim x_d/x_{\text{TA}}$. This value is close to unity at $\mu_{-8} \sim 1$, so we expect the change in the character of the clump formation process near $\mu_{-8} \sim 1$.

In the continuous evaporation approximation the rate of loop mass evaporation due to gravitational radiation is $dM_l/dt = -\Gamma G\mu^2/c$. After integration we have

$$M_l(t) = M_l(t_i) \left(1 - 5 \times 10^{-6} \frac{\mu_{-8} \Gamma_{50}}{\alpha_{0.1}} \left[\frac{t}{t_i} - 1 \right] \right), \quad (4.4)$$

where the $M_l(t_i) = \mu \alpha t_i$ is the initial string mass at the moment of its birth t_i . One need to generalize the evolving seed mass as the fuse of fluctuation growth. The only quantity one need to change is Φ . From the known solutions of the Fridmann equations one has the dependence $t = \tilde{t}(x)$ and by using (3.3) we finally obtain

$$\Phi(x, x_i) = \frac{2 \times 10^{-3} \mu_{-8} \alpha_{0.1}^{-2}}{x_i} \frac{M_l(\tilde{t}(x))}{M_l(\tilde{t}(x_i))}. \quad (4.5)$$

This expression is valid for $\Phi \geq 0$. If formally $\Phi < 0$ we put $\Phi = 0$ in (3.1). This means that the string had totally evaporated (its mass is zero) and the subsequent clump evolution proceeds only under DM self gravity and due to inward velocity boost which appeared before the string decay. The velocity boost leads to the perturbation growth even after full evaporation of the seed loop. The clump virializes with some density $\rho_{\text{cl}}(t_{\text{TA}})$. If the string mass goes to zero after the turnaround the adiabatic expansion of the clump occurs only due to the loop mass remnant $M_l(t_{\text{TA}})$, and the resulting clump density is

$$\rho_{\text{cl}} = \rho_{\text{cl}}(t_{\text{TA}}) \left(\frac{M_{\text{DM}}}{M_l(t_{\text{TA}}) + M_{\text{DM}}} \right)^3 = \frac{\rho_{\text{cl}}(t_{\text{TA}})}{(1 + \Phi(x_{\text{TA}}))^3}. \quad (4.6)$$

In the case $t_d > t_{\text{TA}}$ this density is greater in comparison with density $\rho_{\text{cl}} \simeq 140\rho_{\text{eq}}$ in the fast decay approximation.

5 Numerical results

We solve Eq. (3.1) numerically in the two above approximations. In the approximation of fast decay the loop decay at the moment $t_d = t_i + \tau$. This means that at $t < t_d$ the mass of the string is constant, but at $t > t_d$ the string had totally disappeared (its mass is zero), and the subsequent clump evolution proceeds only under DM self gravity and due to inward velocity boost which appeared before the string decay. The velocity boost leads to the perturbation growth even after full evaporation of the seed loop.

We consider only the most dense central region of the clumps, which gives the main contribution to the annihilation signal. These are regions inside the string volumes. As the first approximation we consider these regions as homogeneous. We find the density of the clump in dependence of x_i and μ . The turnaround moment is calculated numerically from the condition $db/dx = -b/x$ and the solution of (3.1). Clumps density is obtained according to (3.2) and (4.6). If the turnaround moment precedes the loop decay, we put the resulting clump density $\rho = 140\rho_{\text{eq}}$ according to adiabatic invariant argument conservation of [12].

The results of calculations for clumps density in the fast decay approximation are shown at the figure 1. As it was expected from (4.3), the condition $x_{\text{TA}} \simeq x_d$ is satisfied near $\mu_{-8} \sim 1$, and the regime of clump formation changes near $\mu_{-8} \sim 1$ because at larger μ_{-8} the turnaround occurs before the loop decay. The similar figure can be presented for the continuous evaporation approximation, but with smoother surface break and with greater density of the clumps.

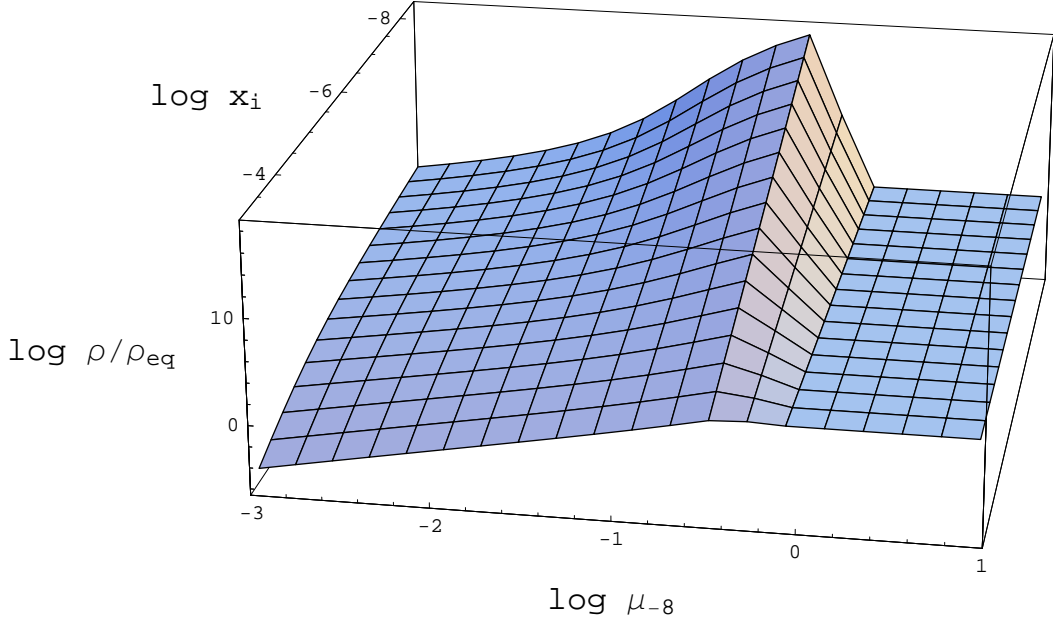


Figure 1. Clump density ρ in the units of density at matter-radiation equality ρ_{eq} in dependence on the loop birth moment x_i and parameter $\mu_{-8} = G\mu/(10^{-8}c^2)$. The break of the surface down to value $\rho = 140\rho_{\text{eq}}$ corresponds to the proximity of turnaround and loop decay moments.

6 Loops and clumps distributions

The length distribution of cosmic strings' loops in the interconnecting network was obtained in [9] in the form

$$dn_{\text{loop}} = \frac{N dl}{c^{3/2} t^{3/2} l^{5/2}}, \quad (6.1)$$

where $N \sim 2$. The evaporating mass cutoff must be superimposed on the distribution (6.1) at the every particular time. If we neglect (temporary) the loop evaporation, then the mass fraction of the universe in the form of loops at the time t_{eq} is

$$\frac{d\rho_l(t_{\text{eq}})}{\rho_{\text{eq}}} = 0.042 \mu_{-8}^{3/2} \left(\frac{M_l}{M_{\odot}} \right)^{-3/2} \frac{dM_l}{M_{\odot}}. \quad (6.2)$$

In terms of cosmological density of clumps (a fraction of DM mass in the form of clumps) the distribution (6.2) (by using (3.3)) can be rewritten as:

$$d\xi_{\text{cl}} \simeq \frac{d\rho_l(t_{\text{eq}})}{\rho_{\text{eq}}} \left(\frac{M_l}{M_{\beta}} \right)^{1/2} P_{\text{lv}}, \quad (6.3)$$

where P_{lv} is given by (2.4). Strings decay but the clumps survive, therefore there is no need to cut of the clumps mass spectrum at the string evaporation scale, and the (6.3) is the real distribution of clumps at MD epoch. The density of these clumps was calculated in the Section 5.

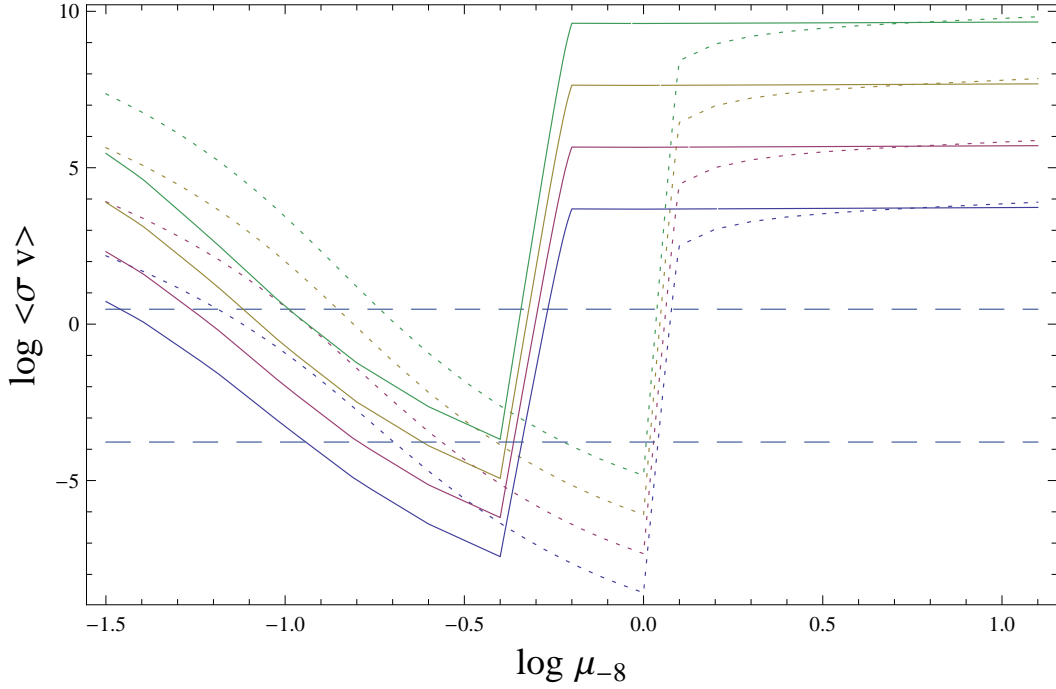


Figure 2. Upper limits on $\langle\sigma v\rangle$ (in units $10^{-26} \text{ cm}^3 \text{ s}^{-1}$) in dependence of the string parameter $\mu_{-8} = G\mu/(10^{-8}c^2)$. The solid lines show the limits for the masses of DM particles (from up to down) $m_\chi = 10 \text{ TeV}$, 1 TeV , 100 GeV and 10 GeV in the fast decay approximation. The limits were obtained from the comparison of the calculated signals and the Fermi-LAT data. The upper and lower horizontal dashed lines show the typical and minimal possible cross-section values, respectively. The dotted lines show the upper limits in the continuous evaporation approximation for the same masses.

The low mass cut of the clumps distribution is determined by the process of kinetic decoupling of the DM particles. At earlier times the DM particles strongly frozen in the radiation and do not move toward the loop. In contrast to the ordinary inflationary density perturbations the diffusion and free streaming effects are not important for the minimum mass of the clumps. This is because the forming clump subjected mainly by the strong gravitational pull of the central loop and evolve nonlinearly long before the equality moment t_{eq} . The kinetic decoupling temperature for ordinary neutralino weakly depends on the particle mass $T_d \propto m_\chi^{1/4}$ and, for example, for $m_{100} \equiv m_\chi/(100 \text{ GeV}) = 1$ and for typical SUSY parameters $T_d \simeq 25 \text{ GeV}$ with corresponding cosmological time $t_d \simeq 1.2 \times 10^{-3} \text{ s}$. The loops which formed at the moment t_d have masses $M_{l,\text{min}} = 2.5 \times 10^{-7} m_{100}^{-1/2} \mu_{-8} \alpha_{0.1} M_\odot$ and the minimum clump's mass is therefore $M_{\text{cl},\text{min}} = M_{l,\text{min}}^{3/2} / M_\beta^{1/2} \simeq 2 \times 10^{-15} m_{100}^{-3/4} \alpha_{0.1}^3 M_\odot$ according to (3.3). These minimum mass clumps can reach densities $\rho_{\text{cl}} \sim 3 \times 10^{-4} \text{ g cm}^{-3}$ if $\mu_{-8} \simeq 0.4$ (see figure 1).

7 DM annihilation

The clumps under consideration have very large densities and the gamma-ray flux from DM annihilation inside the clumps may exceed the observational limits for some values of string parameter μ_{-8} . Let us consider the neutralino (the most popular DM candidate) annihilation

in the clumps. Annihilation rate of neutralino in a single clump $\dot{N}_{\text{ann}} = 2\eta_{\pi^0} 4\pi \langle \sigma v \rangle \int_0^R n_\chi^2 r^2 dr$, where $\eta_{\pi^0} \sim 10$ is the neutral pion multiplicity, n_χ is the number density of particles inside clump, $R \simeq (3M/4\pi\rho)^{1/3}$ and $\langle \sigma v \rangle$ is the annihilation cross-section (averaged product with velocity). We consider the annihilation channel with π^0 productions and decays $\pi^0 \rightarrow 2\gamma$. The cumulative gamma-ray signal from the clumps in the angular direction ψ with respect to Galactic center can be expressed as

$$J_\gamma(E > m_{\pi^0}/2, \psi) = 1.9 \times 10^{-10} \left(\frac{m_\chi}{100 \text{ GeV}} \right)^{-2} \frac{\langle \sigma v \rangle}{10^{-26} \text{ cm}^3 \text{ s}^{-1}} \langle J(\psi) \rangle_{\Delta\Omega}, \quad (7.1)$$

where

$$\langle J(\psi) \rangle_{\Delta\Omega} = \int d\xi_{\text{cl}} \left(\frac{\rho_{\text{cl}}}{0.3 \text{ GeV cm}^{-3}} \right) \int_{l.o.s.} \frac{dL}{8.5 \text{ kpc}} \left(\frac{\rho_H(r)}{0.3 \text{ GeV cm}^{-3}} \right), \quad (7.2)$$

and the last integration goes along the line of sight. For the halo density profile $\rho_H(r)$ we use the NFW profile [15] with the scale $a = 20 \text{ kpc}$, halo mass $M_h = 10^{12} M_\odot$ and virial radius $R_h = 200 \text{ kpc}$. The lower mass limits in the integration $d\xi_{\text{cl}}$ was estimated in the previous section. This limit weakly depends on m_χ through the $T_d(m_\chi)$ dependence. We took $M_{l,\text{max}} \simeq 1.6 \times 10^3 \mu_{-8}^3 M_\odot$ (this seed mass corresponds to the clump's formation time near t_{eq}) as the upper limits of the integration, and the dependence of the final result on $M_{l,\text{max}}$ is weak.

We compare the calculated signals with Fermi-LAT diffuse extragalactic gamma-ray background $J_{\text{obs}}(E > m_{\pi^0}/2) = 1.8 \times 10^{-5} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ [16]. To obtain the most conservative limit we compare J_{obs} with the calculated signal in the anti-center direction $\psi = \pi$. It gives the upper limit on $\langle \sigma v \rangle$ in dependence of $\mu_{-8} = G\mu/(10^{-8} c^2)$. The results are shown at figure 2. We consider the several values of the neutralino mass: $m_\chi = 10 \text{ TeV}$, 1 TeV , 100 GeV and 10 GeV . The mass m_χ influences the result mainly through the factor m_χ^{-2} under the integral (7.1) and through the low mass limit in the loops distribution, which weakly depends on m_χ .

For example, for the mass $m_\chi = 100 \text{ GeV}$ in the case of typical neutralino cross-section $\langle \sigma v \rangle \simeq 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ (this value corresponds to the thermal production of DM particles) the limit excludes the range of parameters $0.05 < \mu_{-8} < 0.51$ in fast decay approximation and $0.1 < \mu_{-8} < 1.16$ in the continuous evaporation approximation. If we take the minimal allowed value $\langle \sigma v \rangle = 1.7 \times 10^{-30} m_{100}^{-2} \text{ cm}^3 \text{ s}^{-1}$ [17] and $m_\chi = 100 \text{ GeV}$ the excluded regions are $0.16 < \mu_{-8} < 0.43$ and $0.27 < \mu_{-8} < 1.07$ in the same two approximations.

8 Conclusions

In this work we explore the possibility of dark matter annihilation in the dense cores of clumps that were seeded by cosmic string loops before the matter-radiation equality. We calculate the evolution of the clumps around evaporating loops. Only the low-velocity loops result in the clumps formation. At the same time, even the low-velocity tail of the loop distribution produces DM clumps with the observable signature in the annihilation products. The adiabatic argument conservation doesn't prevent the formation of clumps with densities $\rho_{\text{cl}} \gg 140\rho_{\text{eq}}$, if the decay of the loops occurs before the time of the clumps virialization. Therefore the DM clumps produced by the loops can be the very dense objects with high cumulative luminosity in the gamma-rays.

The combined constraints on the loops parameters (μ and the distribution over lengths) and parameters of DM particles were obtained. For the 100 GeV neutralino DM the range $5 \times 10^{-10} < G\mu/c^2 < 5.1 \times 10^{-9}$ was excluded because of the huge gamma-ray annihilation signal above the Fermi-LAT data for these parameters. Along with the preferable neutralino dark matter candidate with the mass 100 GeV, we consider the masses 10 TeV, 1 TeV, and 10 GeV and explore the two limiting assumptions about the loop evolution: fast decay and continuous evaporation approximations. The corresponding constraints on the annihilational cross-section are shown at the figure 2. We restrict ourself only by the preferable value $\alpha = 0.1$. The results will change for different α .

In the case of the cosmic superstrings, the reconnection probability can be $\ll 1$, resulting in the much higher number density of loops. This could lead to even stronger constraints in comparison with the presented in this paper.

The Fermi-LAT data are used as the upper limit. In principle the annihilation of DM in the clumps can explain the observed signal for the particular values, for example $G\mu/c^2 \simeq 5 \times 10^{-10}$. The necessity of the DM annihilation can arise if the ordinary astrophysical sources give too small signal in comparison with the observations.

Acknowledgments

We thank A. Vilenkin for the very useful suggestions and discussion. This work was supported by the grants of the Russian Leading scientific schools 3517.2010.2 and Russian Foundation of the Basic Research 10-02-00635.

References

- [1] A. Vilenkin and E.P.S. Shellard, *Cosmic strings and other topological defects*, Cambridge University Press, Cambridge U.K. (1994).
- [2] A. Vilenkin, *Cosmic strings: progress and problems in Inflating Horizons of Particle Astrophysics and Cosmology*, ed. by H. Suzuki, J. Yokoyama, Y. Suto and K. Sato (Universal Academy Press, Tokyo, 2006), [arXiv:hep-th/0508135v2].
- [3] V. Vanchurin, K.D. Olum and A. Vilenkin, *Scaling of cosmic string loops*, *Phys. Rev. D* **74** (2006) 063527, [arXiv:gr-qc/0511159v4].
- [4] J.J. Blanco-Pillado, K. Olum and B. Shlaer, *Large parallel cosmic string simulations: New results on loop production*, [arXiv:1101.5173 [astro-ph]].
- [5] C.J.A. Martins and E.P.S. Shellard, *Phys. Rev. D* **73** (2006) 043515, [arXiv:astro-ph/05111792].
- [6] C. Ringeval, M. Sakellariadou and F. Bouchet, *JCAP* **0702** (2007) 023, [arXiv:astro-ph/0511646].
- [7] L. Pogosian, I. Wasserman and M. Wyman, *On vector mode contribution to CMB temperature and polarization from local strings*, [arXiv:astro-ph/0604141v1].
- [8] J.L. Christiansen et al., *Search for cosmic strings in the Great Observatories Origins Deep Survey*, *Phys. Rev. D* **77** (2008) 123509, [arXiv:0803.0027v2 [astro-ph]].
- [9] K.D. Olum and A. Vilenkin, *Reionization from cosmic string loops*, *Phys. Rev. D* **74** (2006) 063516, [arXiv:astro-ph/0605465].
- [10] B. Abbott et al, *First LIGO search for gravitational wave bursts from cosmic (super)strings*, *Phys. Rev. D* **80** (2009) 062002, [arXiv:0904.4718v2 [astro-ph.CO]].

- [11] R. van Haasteren et.al., *Placing limits on the stochastic gravitational-wave background using European Pulsar Timing Array data*, [arXiv:1103.0576 [astro-ph]].
- [12] E.W. Kolb and I.I. Tkachev, *Large-amplitude isothermal fluctuations and high-density dark-matter clumps*, *Phys. Rev. D* **50** (1994) 769, [arXiv:astro-ph/9403011v1].
- [13] B. Allen and E.P.S Shellard, *Cosmic-string evolution: A numerical simulation*, *Phys. Rev. Lett.* **64** (1990) 119.
- [14] T. Vachaspati and A. Vilenkin, *Gravitational radiation from cosmic strings*, *Phys. Rev. D* **31**, 3052 (1985); J. M. Quashnock and D. N. Spergel, *Gravitational self-interactions of cosmic strings*, *Phys. Rev. D* **42** (1990) 2505.
- [15] J.F. Navarro, C.S. Frenk and S.D.M. White, *The Structure of Cold Dark Matter Halos*, *Astrophys. J.* **462** (1996) 563, [arXiv:astro-ph/9508025v1].
- [16] A.A. Abdo et al., *The Spectrum of the Isotropic Diffuse Gamma-Ray Emission Derived From First-Year Fermi Large Area Telescope Data*, *Phys. Rev. Lett.* **104** (2010) 101101, [arXiv:1002.3603v1 [astro-ph.HE]].
- [17] V. Berezhinsky, A. Bottino and G. Mignola, *On neutralino stars as microlensing objects*, *Phys. Lett. B* **391** (1997) 355, [arXiv:astro-ph/9610060v1].